

# DUST EXTINCTION AND METALLICITIES OF STAR-FORMING LYMAN ALPHA EMITTING GALAXIES AT LOW REDSHIFT<sup>1</sup>

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## ABSTRACT

We present the results of an optical spectroscopic study of 12 *GALEX*-discovered star-forming Ly $\alpha$  emitting galaxies (LAEs) at  $z \sim 0.3$ . We measure the emission line fluxes from these galaxies by fitting their observed spectra to stellar population models in order to correct for underlying stellar absorption. We revisit earlier stellar population model fitting results, finding that excluding now-known AGNs lowers the typical stellar population age and stellar mass of this sample to  $\sim 300$  Myr and  $\sim 4 \times 10^9 M_{\odot}$ , respectively. We calculate their dust extinction using the Balmer decrement, and find a typical visual attenuation of  $A_V \sim 0.3$  mag, similar to that seen in many high-redshift LAEs. Comparing the ratio of Ly $\alpha$ /H $\alpha$  and the Ly $\alpha$  equivalent widths to the measured dust extinction, we find that the ISMs in these objects appear to be neither enhancing nor seriously attenuating the Ly $\alpha$  equivalent widths, as would be the case in a quasi-clumpy ISM. Lastly, we perform a detailed analysis of the gas-phase metallicities of these galaxies, and we find that most galaxies in our sample have  $Z \lesssim 0.4 Z_{\odot}$ . We find that at a fixed stellar mass, these low-redshift LAE analogs are offset by  $\sim 0.6$  dex lower in metallicity from the general galaxy population at similar redshifts based on the local mass-metallicity relationship. This implies that galaxies with Ly $\alpha$  in emission may be systematically more metal poor than star-forming galaxies at the same stellar mass and redshift, similar to preliminary results at  $z \sim 2$ .

*Subject headings:* galaxies: evolution

## 1. INTRODUCTION

Galaxies selected on the basis of a bright Ly $\alpha$  emission line were originally thought to be indicative of primordial galaxies undergoing their first burst of star-formation (Partridge & Peebles 1967), though they have recently been shown to be a complicated group of objects. Studies utilizing the technique of spectral energy distribution (SED) fitting have shown that typical narrowband-selected Ly $\alpha$  emitting galaxies (LAEs) appear to be predominantly young and low-mass, with ages  $< 100$  Myr and masses  $\lesssim$  a few  $\times 10^9 M_{\odot}$  (e.g., Gawiser et al. 2006; Finkelstein et al. 2007; Pirzkal et al. 2007; Lai et al. 2007; Nilsson et al. 2007). However, in many cases these galaxies also appear to contain some dust, thus they are likely not primordial in nature (e.g., Pirzkal et al. 2007; Lai et al. 2008; Finkelstein et al. 2008, 2009d; Pentericci et al. 2009). In addition, a small fraction of LAEs appear to be more evolved with ages of  $\sim 0.5$  Gyr and masses of  $\sim 10^{10} M_{\odot}$ , suggesting that there may be multiple populations of LAEs, or perhaps a tail in the distribution of LAE properties toward more evolved objects (e.g., Finkelstein et al. 2009d; Lai et al. 2008; Pentericci et al. 2009). These more evolved LAEs provide a link to the characteristically more evolved Lyman break galaxies (LBGs; e.g.,

Kornei et al. 2010).

While the stellar masses of galaxies can be reasonably constrained from SED fitting, the remaining properties suffer from degeneracies, and can be poorly constrained in the absence of rest-frame optical detections, especially at high-redshift. Specifically, the derived ages, dust extinctions and metallicities are only weakly constrained, as they all result in a reddening of the integrated light from a given galaxy. While photometry spanning the 4000 Å break can improve the fidelity of age estimates, the extinction can typically only be roughly constrained, and the metallicity not constrained at all. In order to obtain more robust estimates of the physical make-up of LAEs, direct measurements of the extinction and metallicity are necessary. At low redshift, this is typically done using measurements of the flux of nebular emission lines in the rest-frame optical, e.g., using Balmer line ratios to measure the dust extinction, and ratios of metal lines to measure the gas-phase metallicities (e.g. Kobulnicky et al. 1999; Pettini & Pagel 2004). These analyses are not currently possible at  $z \gtrsim 3$ , as these diagnostic lines are shifted into the mid-infrared. From  $2 < z < 3$ , these measurements are possible using near-infrared spectroscopy on 8–10m class telescopes (e.g., Erb et al. 2006a; Finkelstein et al. 2010). However, samples of LAEs at these redshifts are only now being compiled, and the required integration times are long.

Presently, we can use low-redshift analogs to try to understand LAEs at high-redshift. Locally, the Ly $\alpha$  properties of star-forming galaxies have been studied in great detail. It was found that Ly $\alpha$  emission can correlate with bright UV (and H $\alpha$ ) emission in some regions of a galaxy, but not in others. It was also shown that Ly $\alpha$  can escape from galaxies even with a significant dust content, especially if outflows are present in the interstellar medium (ISM; e.g. Kunth et al. 1998; Hayes et al. 2007; Atek et al. 2008; Östlin et al. 2009). These results indicate that the mechanisms which regulate

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$\text{Ly}\alpha$  escape are complicated, which is an important detail to consider when interpreting the results of high-redshift LAEs.

A little further out, Deharveng et al. (2008) published the discovery of  $\sim 100$  LAEs at  $z \sim 0.3$  using the space-based *Galaxy Evolution Explorer* (GALEX) telescope. A study of their luminosity function found that LAEs at low redshift are more rare and less luminous in  $\text{Ly}\alpha$  than at  $z > 3$  (Deharveng et al. 2008; Cowie et al. 2010). In a followup study, Finkelstein et al. (2009a) studied the stellar populations of a subsample of 30 of these LAEs, finding that they appear older and more massive than typical high-redshift LAEs. A higher fraction of low-redshift LAEs appear to host active galactic nuclei (AGN), from  $\sim 15 - 40\%$  (Finkelstein et al. 2009b; Scarlata et al. 2009; Cowie et al. 2010). Cowie et al. (2010) compare the metallicities from the ratio of  $[\text{N II}]/\text{H}\alpha$  emission from  $z \sim 0.3$  LAEs to those of  $z \sim 0.3$  continuum-selected galaxies, finding that while the distributions overlap, the LAEs extend to lower metallicities. Lastly, Atek et al. (2009) used  $\text{H}\alpha$  and  $\text{H}\beta$  observations from a subset of these galaxies to study the  $\text{Ly}\alpha$  escape fraction, finding clear evidence for a decreased escape fraction with increased extinction, although some galaxies do exhibit a  $\text{Ly}\alpha$  escape fraction greater than the continuum, which could imply a clumpy ISM geometry (e.g. Neufeld 1991; Finkelstein et al. 2009d).

In this Paper we present the spectra of our sample of 12 GALEX LAEs in the Extended Groth Strip (EGS) which are dominated by star-formation activity, first analyzed in Finkelstein et al. (2009a) via SED-fitting, and later shown to be devoid of AGN activity in Finkelstein et al. (2009b). In §2 of this Paper, we present the full spectra of every object in our sample, along with their measured line fluxes. In §3, we revisit the typical ages and masses of this sample, comparing to what we earlier derived in Finkelstein et al. (2009a) when knowledge of AGN activity was unknown. We discuss the dust properties and insights into the ISM geometries of our sample in §4, and in §5, we present metallicity measurements with three separate metallicity indicators, as well as examine the mass-metallicity relation, and the implications it has on LAEs near and far. In §6 we present our conclusions. Where applicable, we assume  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ .

## 2. DATA

### 2.1. Observations and Data Reduction

We obtained spectroscopy of 23 of the 27 previously analyzed LAEs from Finkelstein et al. (2009a) in the EGS, using the Hectospec spectrograph with the 6.5m MMT telescope (all 27 could not be observed in one configuration, thus this choice of 23 allowed the most simultaneous observations). Hectospec is a multi-fiber spectrograph, with 300  $1.5''$  fibers covering a  $1^\circ$  diameter field-of-view at the f/5 focus (Fabricant et al. 2005). We acquired spectroscopy for our sample using MMT+Hectospec observations, taken in queue mode on 19 March 2009, obtaining 120 minutes of low-resolution grating spectroscopy, which provides spectral coverage from  $\sim 3650 - 9200 \text{ \AA}$ , with a spectral resolution of  $\sim 5 \text{ \AA}$ . The seeing throughout the night was consistently between  $0.6'' - 0.8''$ , and thus much smaller than the Hectospec fibers.

There are two primary pipelines for the reduction of Hectospec data, IDL and IRAF<sup>1</sup> based. We chose to use the

IRAF-based pipeline, as it has recently been ported for external use as External SPECROAD (or E-SPECROAD)<sup>2</sup>. The reduction consists of three tasks: The first, called as `specroad`, makes the master bias, flat and dark frames. The next task, `specroadcal`, traces the fibers across the chips, creates a dispersion function, and creates the fiber throughput correction. `Specroadcal` prompts the user to interactively fit a wavelength solution, using lines of helium, neon and argon. We obtained rms residuals from  $0.1 - 0.15 \text{ \AA}$  using 55 lines spanning the entire wavelength range. `Specroadcal` then applies a dispersion correction to the flat frame. The last task, `specroadobj`, reduces all of the object data, using the calibrations made with the previous two tasks, and subtracting the sky which was computed from among the six closest of  $\sim 50$  sky fibers placed throughout the Hectospec field (where the flux variation between the fibers was small). The software then splits off the 300 fibers into individual fits files, which we used moving forward. Each of these files contains the wavelength, flux, and flux error array for the specific fiber, where the error spectrum is computed from a variance array that was created from the raw frame and processed through the same reduction steps.

In addition to our primary targets, we also placed fibers on 12 F-type stars from the Sloan Digital Sky Survey, which we used to flux calibrate the data. These stars are good calibrators, as they are a compromise between strong hydrogen lines in hotter stars and other atomic lines in cooler stars. For each star, we scaled up a Kurucz (1993) F0V star model to match the fluxes, integrating the model spectrum through the Sloan Digital Sky Survey (SDSS)  $g'$ ,  $r'$  and  $i'$  filter curves (these three bands were fully encompassed by our wavelength range). We then computed a scale factor for each filter by dividing the model flux from the SDSS catalog flux for the given star. A final scale factor was computed as the mean of the scale factor from the three filters. This scale was then multiplied into the model spectrum. Finally, a calibration array was computed as the scaled up Kurucz model divided by the observed stellar spectrum. This was repeated for each star, with a final calibration array coming from the mean of each of the 12 observed stars. We estimated the accuracy of our flux calibration as the standard deviation of the mean of these 12 observations, which we found to be relatively small, at  $< 8\%$ . The final calibration array was multiplied into our object spectra, which in addition to flux calibration also corrects for the grating transmission function. The full spectra of all 12 star-forming LAEs are shown in Figure 1.

### 2.2. Spectral Fitting

We measure the emission-line fluxes of the objects in our sample using the method described by Moustakas et al. (2010). Briefly, we fit a non-negative linear combination of Bruzual & Charlot (2003) population synthesis models with instantaneous burst ages ranging from 5 Myr to 10.5 Gyr (the age of the Universe at  $z \sim 0.25$ ), assuming the Chabrier (2003) initial mass function from  $0.1 - 100 M_\odot$ . Motivated by the fact that the gas-phase metallicities of these objects are sub-solar (see §5), we assume a fixed stellar metallicity of  $Z = 0.004$  ( $20\% Z_\odot$ ); however, we have verified that using

(NOAO), which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

<sup>2</sup> E-SPECROAD is available at:

<http://iparrizar.mnstate.edu/~juan/research/ESPECROAD/index.php>

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory

TABLE 1  
OBJECT PROPERTIES AND MEASURED LINE FLUXES

Object	RA (J2000)	Dec (J2000)	Redshift	Ly $\alpha$ $\lambda 1216$	[O II] $\lambda 3727$	H $\beta$ $\lambda 4861$	[O III] $\lambda 4959$	[O III] $\lambda 5007$	H $\alpha$ $\lambda 6563$	[N II] $\lambda 6583$
EGS7	215.17155	53.11394	0.1996	16.1	$9.58 \pm 0.12$	$5.29 \pm 0.08$	$7.79 \pm 0.04$	$24.03 \pm 0.11$	$19.77 \pm 0.20$	$0.89 \pm 0.11$
EGS8	214.43095	52.46829	0.2078	76.7	$2.25 \pm 0.08$	$0.91 \pm 0.06$	$0.86 \pm 0.02$	$2.52 \pm 0.07$	$2.78 \pm 0.10$	$< 0.10$
EGS10	214.55878	52.39549	0.2102	12.3	$4.80 \pm 0.12$	$1.74 \pm 0.06$	$2.01 \pm 0.03$	$5.93 \pm 0.08$	$6.02 \pm 0.16$	$< 0.12$
EGS11	214.52132	52.75198	0.2440	27.8	$2.05 \pm 0.09$	$0.84 \pm 0.06$	$0.28 \pm 0.01$	$1.06 \pm 0.07$	$2.98 \pm 0.10$	$0.84 \pm 0.11$
EGS12	214.70103	52.29891	0.2395	15.2	$2.59 \pm 0.08$	$1.01 \pm 0.05$	$0.70 \pm 0.02$	$2.12 \pm 0.06$	$3.45 \pm 0.12$	$0.44 \pm 0.07$
EGS13	214.22613	52.41111	0.2462	35.9	$10.52 \pm 0.13$	$4.59 \pm 0.08$	$2.73 \pm 0.03$	$8.43 \pm 0.10$	$17.95 \pm 0.21$	$2.59 \pm 0.17$
EGS19	215.18036	52.71884	0.2466	28.7	$3.13 \pm 0.08$	$1.46 \pm 0.06$	$0.47 \pm 0.02$	$1.40 \pm 0.06$	$5.10 \pm 0.15$	$1.51 \pm 0.18$
EGS20	214.81132	52.39066	0.2524	14.2	$4.65 \pm 0.09$	$1.53 \pm 0.07$	$1.66 \pm 0.03$	$4.80 \pm 0.08$	$4.43 \pm 0.11$	$< 0.21$
EGS21	215.18599	52.83513	0.2515	25.3	$1.39 \pm 0.08$	$0.77 \pm 0.07$	$0.08 \pm 0.02$	$0.25 \pm 0.06$	$2.62 \pm 0.16$	$1.23 \pm 0.11$
EGS22	214.30073	52.59907	0.2607	20.8	$1.47 \pm 0.08$	$0.64 \pm 0.08$	$0.13 \pm 0.02$	$0.40 \pm 0.06$	$2.93 \pm 0.18$	$< 0.14$
EGS23	215.35227	52.65558	0.2578	18.0	$9.75 \pm 0.11$	$4.22 \pm 0.09$	$4.09 \pm 0.04$	$12.43 \pm 0.10$	$15.27 \pm 0.20$	$1.66 \pm 0.14$
EGS25	214.73180	52.82437	0.2630	20.1	$13.89 \pm 0.14$	$8.84 \pm 0.10$	$11.81 \pm 0.04$	$42.91 \pm 0.17$	$31.02 \pm 0.24$	$1.66 \pm 0.13$

NOTE. — All line fluxes are in units of  $10^{-16}$  erg s $^{-1}$  cm $^{-2}$ . When [N II] is not detected, we report the  $3\sigma$  upper limit, as measured from placement of mock lines in the spectra. The Ly $\alpha$  line fluxes are measured from GALEX spectra in Deharveng et al. (2008) (which have a characteristic uncertainty of  $4 \times 10^{-16}$  erg s $^{-1}$  cm $^{-2}$ ). The redshift is the weighted mean of all lines detected at  $\geq 3\sigma$  significance, with a characteristic error  $\Delta z \sim 0.00001$ . The last column is the best-fitting extinction on the stellar continuum from the spectral fitting described in §2.2.

solar-metallicity templates has a negligible effect on the derived line-strengths. After subtracting the best-fitting stellar continuum from the data, we are left with a pure emission-line spectrum self-consistently corrected for underlying stellar absorption. Finally, we fit all the emission lines simultaneously using Gaussian line-profiles. In Figure 2 we illustrate our fitting method for one object in our sample, EGS19. In the top panel we plot the observed spectrum (light grey), the best-fitting continuum model (black), and the residual emission-line spectrum (dark grey). We show the full best-fitting emission-line model spectrum (dark red) in the top panel, and in the lower panel we zoom into the emission lines of interest. The lower, middle panel in particular emphasizes the importance of correcting the H $\beta$  line-strength for underlying stellar absorption using this kind of technique (see, e.g., Walcher et al. 2010, for a recent review).

The [N II] emission line was not detected in four of our objects. In these cases, we computed upper limits to their line fluxes by adding in mock emission lines to the spectrum, and repeatedly decreasing their line strength until the signal-to-noise dropped below  $3\sigma$ . We found that on average, the  $3\sigma$  line flux limits were  $\approx 1.0 \times 10^{-17}$  erg s $^{-1}$  cm $^{-2}$ . In the analysis below, we use the  $3\sigma$  upper limits as the line fluxes for these lines. Additionally, the [O III]  $\lambda 4959$  line was not detected in two objects (EGS21 and EGS22). This is understandable as these two objects had the lowest [O III]  $\lambda 5007$  fluxes, though both were detected at  $> 4\sigma$ . We thus set the [O III]  $\lambda 4959$  flux to be  $0.336 \times$  the [O III]  $\lambda 5007$  flux (the theoretical line flux ratio from Storey & Zeppen (2000)) for these two objects. We note that out of the remaining 10 objects, all but two have their ratio of [O III] flux ratios at  $< 3\sigma$  of the theoretical value. The line fluxes for the measured lines which are relevant to our analysis are given in Table 1.

### 3. THE AGES AND MASSES OF STAR-FORMING LOW-REDSHIFT LAES

In Finkelstein et al. (2009a) we derived the stellar population properties of the parent sample of 30 LAEs via spectral energy distribution (SED) fitting, from which we drew the 23 objects observed with Hectospec, including the 12 confirmed star-formation-dominated galaxies presented here. As this was prior to the spectroscopic observations presented in this Paper (and Finkelstein et al. (2009b)), no knowledge of

AGNs or line emission was accounted for in the fitting process. The model templates used in this procedure account only for stellar emission, thus both AGN continuum emission and nebular line emission can cause incorrect fits. Although in this paper we exclude the known AGNs from our analysis, it is still prudent to revisit the SED-fitting results as the stellar masses are key to our analysis below.

We have re-performed the SED fitting using the same procedure outlined in Finkelstein et al. (2009a). However, here we use the updated 2007 version of the models of Bruzual & Charlot (2003). In brief, we generate a suite of metals, varying the metallicity ( $0.02 \leq Z \leq 2.5 Z_{\odot}$ ), star-formation history (exponentially decaying with  $10^5 \leq \tau_{SFH} \leq 10^{9.6}$ ), stellar population age ( $10 \text{ Myr} - t_{\text{universe}}[z]$ ), dust extinction ( $0 \leq A_V \leq 1.6 \text{ mag}$ ) and the ISM clumpiness parameter  $q$  ( $0 \leq q \leq 10$ ); where  $q = \tau_{Ly\alpha}/\tau_{\text{continuum}}$ . We fit this suite of models to our observations; GALEX far-ultraviolet and near-ultraviolet (FUV and NUV, respectively), CFHT Legacy Survey  $u'$ ,  $g'$ ,  $r'$ ,  $i'$  and  $z'$ , and the GALEX Ly $\alpha$  line flux. We find the best-fit model by comparing flux ratios of all bands to the  $u'$ -band (i.e. colors), and calculate the stellar mass of the best-fit model by a weighted mean of the observed fluxes to the fluxes of the best-fit model. Uncertainties on the best-fit parameters (excepting stellar mass) were computed via a Bayesian likelihood analysis (Kauffmann et al. 2003), where the probability distribution is related to the full  $\chi^2$  array via  $P \propto e^{-\chi^2/2}$ . The  $\chi^2$  array is five-dimensional – one for each of our free parameters (5 metallicities  $\times$  5 SFHs  $\times$  124 ages  $\times$  21 values of extinction  $\times$  10 values of  $q$ ). Using age as an example, the probability of a given object having a given age is simply the (normalized) total of  $P$  over all other free parameters. As the mass is determined after the selection of the best-fit model, we determine the uncertainty on the masses via  $10^2$  Monte Carlo simulations. The emission-line subtracted object magnitudes, best-fit stellar population ages, stellar masses and dust extinction, as well as the 68% confidence ranges on these parameters are given in Table 2.

Histograms comparing our best-fit stellar population ages and stellar masses are shown in Figure 3, compared to the results for the full sample from Finkelstein et al. (2009a). While our earlier study found a number of objects with ages in excess of a Gyr, those primarily appear to be dominated by

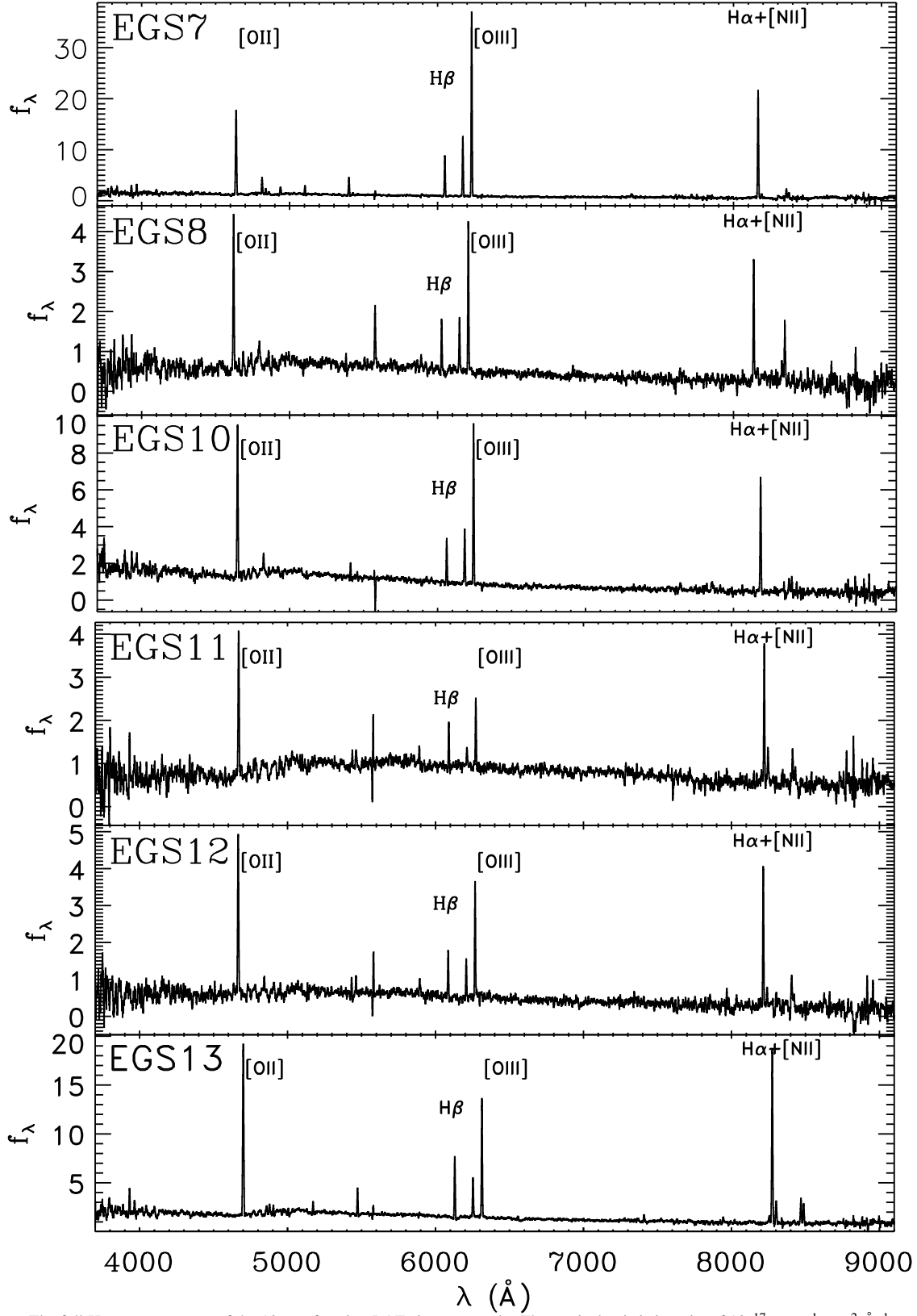


FIG. 1.— The full Hectospec spectra of the 12 star-forming LAEs in our sample. The vertical axis is in units of  $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ , and the reader should note that the vertical scale varies from spectrum to spectrum. The typical observed line width is  $\sim 6$   $\text{\AA}$ . In some cases the 5577  $\text{\AA}$  atmospheric line is poorly subtracted, and should be ignored.

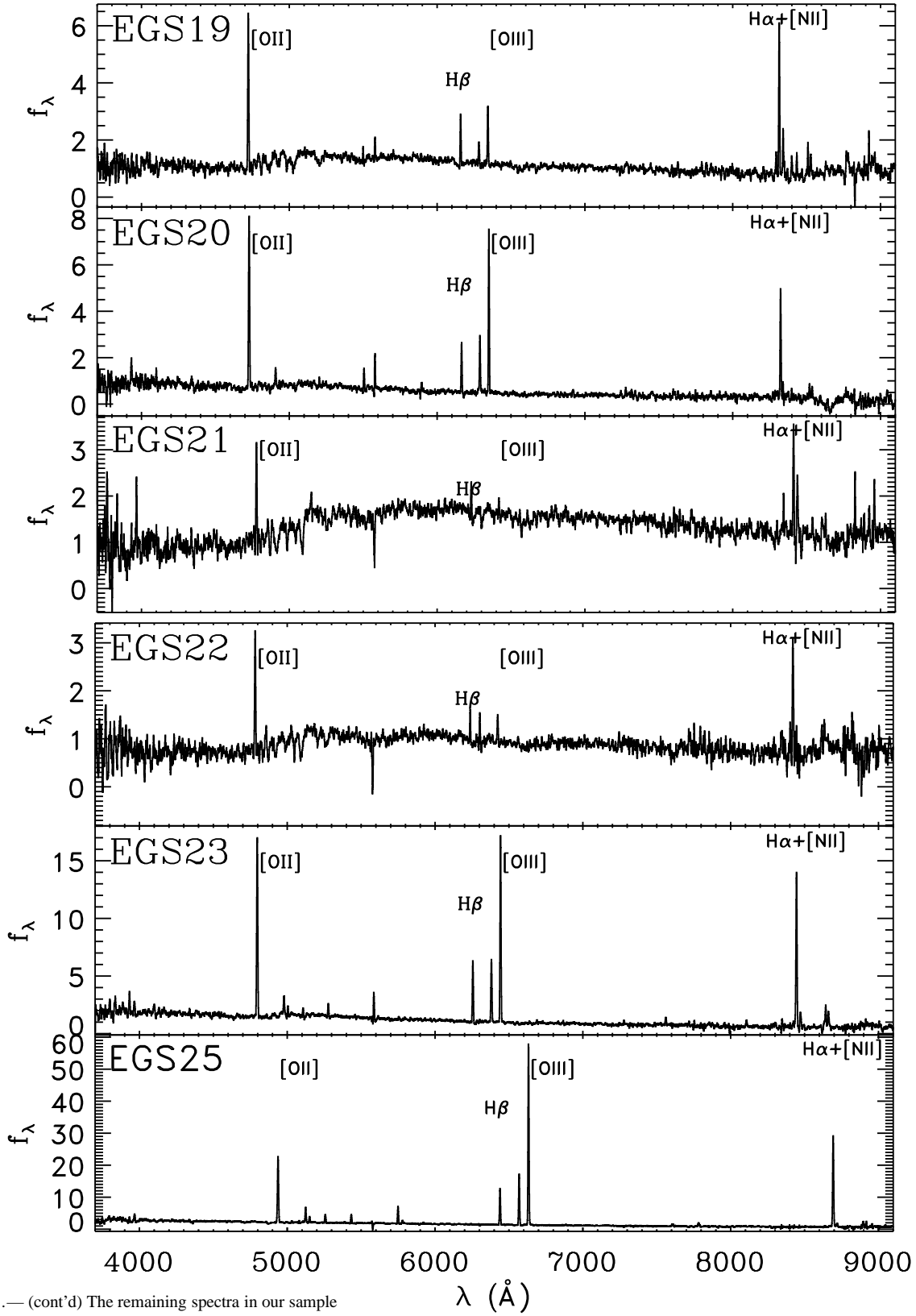


FIG. 1.— (cont'd) The remaining spectra in our sample

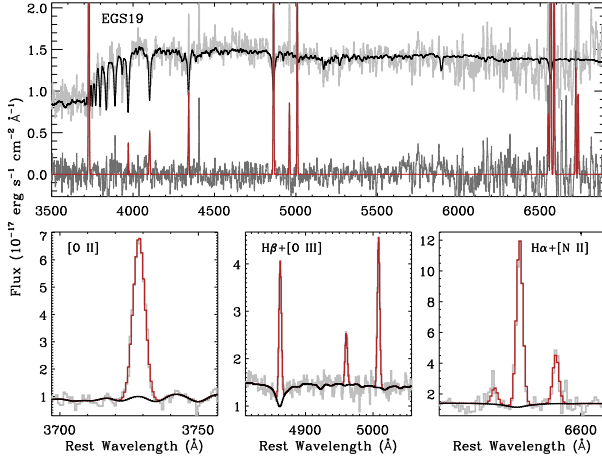


FIG. 2.— An example of the emission-line fitting method on EGS19. The top panel shows our observed spectrum in gray (smoothed by a 5-pixel boxcar), with the best-fitting spectral model shown as the black curve. The underlying emission line spectrum, after subtracting the stellar continuum, is shown in red. The bottom three panels show the regions around some of the lines of interest to our study. Of note is the strong stellar Balmer-line absorption. Correcting for this underlying absorption is crucial to an accurate measurement of the Balmer decrement.

AGN-hosting LAEs, thus the ages may be unreliable. We find that the updated ages for our star-forming LAE sample are primarily between 100 – 1000 Myr, with a median of  $\sim 300$  Myr. We find a similar result for the stellar masses, shown in the right-hand plot of Figure 3, in that the many LAEs with derived stellar masses  $> 10^{10} M_{\odot}$  appear to be dominated by AGN hosts, and that the star-forming LAEs in our current sample have masses  $\sim 10^9 - 10^{10} M_{\odot}$  (with a median of  $4 \times 10^9 M_{\odot}$ ). While these low-redshift LAEs are older and more massive than typical narrowband selected LAEs, they are similar to those of the more evolved, rarer, LAEs seen at high redshift (e.g., Finkelstein et al. 2009d; Lai et al. 2008; Pentericci et al. 2009). However, we do caution that the derived ages are highly uncertain, as although many objects have best-fit ages on the order of a few hundred Myr, the uncertainties on these derived ages are high - sometimes orders of magnitude. As shown in Table 2, the uncertainties on the stellar masses are much smaller, and we use these best-fit masses with their uncertainties in our metallicity analysis in §5.

#### 4. DUST EXTINCTION AND THE ISM

Using the Balmer decrement we can measure the level of dust extinction in our galaxies, providing a much more robust estimate than that derived from SED fitting (listed in Table 2), which is subject to a number of degeneracies. Traditionally, this is done by measuring the ratio of  $H\alpha/H\beta$ , and then comparing to the theoretical ratio, which we take as  $H\alpha/H\beta = 2.86$  (Osterbrock 1989). Any increase in this ratio over the theoretical value is likely due to dust, and, assuming an extinction law, one can compute the color excess. Table 3 tabulates the extinction results assuming the Calzetti et al. (2000) starburst extinction law. The computed color excesses for our objects range from  $0 \lesssim E(B-V)_g \lesssim 0.4$ , with 10/12 objects having  $E(B-V)_g$  significantly greater than zero (at  $1\sigma$  significance; 9/12 at  $2\sigma$ ). We converted the color excess on the nebular emission to an extinction on the stellar continuum as-

suming that  $E(B-V)_{\text{stellar}} = 0.44 E(B-V)_{\text{gas}}$ , as has been found locally (Calzetti et al. 2000). We then converted to the stellar attenuation in the V-band via the adopted attenuation curve. The derived attenuation on the stellar continuum ranges from  $A_V = 0 - 0.7$ , with a mean  $A_V \sim 0.3$ . Comparing the derived attenuations from the Balmer decrement to those from the photometric SED fitting (listed in Table 2), we find excellent agreement, as the difference in attenuation for 9/12 galaxies are smaller than their combined  $1\sigma$  uncertainties. This implies that in this sample of galaxies the conversion used from gas extinction to stellar extinction is accurate, and thus that the nebular emission lines are more extinguished than the stellar continuum. However, the uncertainties on the Balmer-decrement-derived attenuations are much smaller than those from SED fitting, highlighting the advantage of spectroscopy.

Atek et al. (2009) studied the  $\text{Ly}\alpha$  escape fraction in LAEs from the  $z \sim 0.3$  sample of Deharveng et al. (2008), obtaining spectroscopic measurements of objects from the Chandra Deep Field - South (CDFS) and ELAIS-S1 fields. As part of their analysis, they also computed the dust extinction using the ratio of  $H\alpha/H\beta$ . From their Figure 2, they found values of the color excess from  $-0.3 < E(B-V) < 0.5$ , covering roughly the same range of color excess values as we find in our independent sample. Atek et al. (2009) find that 12/21 of their objects are consistent with  $E(B-V) > 0$ . Scarlata et al. (2009) also studied  $z \sim 0.3$  LAEs, obtaining optical spectroscopy of 31 galaxies drawn from the Deharveng et al. (2008) EGS, NGPDWS and SIRTFFL samples, with their EGS sample including four objects in our sample of 12 star-forming galaxies. They do not compute the dust extinction, but to facilitate comparison we have computed the color excess based on their tabulated  $H\alpha$  and  $H\beta$  fluxes for the 20 objects which have 3  $\sigma$  detections of both emission lines. Their objects have a range of  $-0.05 < E(B-V) < 0.74$ , with 11/20 objects consistent with  $E(B-V) > 0$  at  $> 1\sigma$ . While both Atek et al. (2009) and Scarlata et al. (2009) find a slightly smaller fraction of objects with significant dust attenuation than we do, this difference is likely due to the small number of objects analyzed in all three studies, as well as the large uncertainties on the extinction in general. We note that Atek et al. (2009) used the extinction curve of Cardelli et al. (1989). Had we adopted this curve, we would have found higher values of the color excess, though the derived attenuation would be similar to what is reported in Table 2.

While many high-redshift LAEs typically have derived non-zero extinctions, these are inferred from SED fitting. As discussed in Finkelstein et al. (2009a) and §3, the galaxies in our sample are more evolved than typical narrowband selected LAEs at high redshift. Thus, it is interesting to compare the mean value of  $A_V \sim 0.3$  mag measured here to high-redshift LAEs. While Gawiser et al. (2006) derived no dust extinction in LAEs at  $z \sim 3.1$ , others have frequently found evidence for dust in typical narrowband-selected LAEs. Pirzkal et al. (2007) found  $A_V = 0 - 0.6$  mag in LAEs at  $z \sim 5$ , Lai et al. (2007) found  $A_V = 0.4 - 1.7$  mag in LAEs at  $z \sim 5.7$ , and Finkelstein et al. (2009d) found  $A_V = 0.1 - 1.1$  mag in LAEs at  $z \sim 4.5$ . Thus, though it appears that although high-redshift LAEs are on average younger and lower mass, many of them appear to contain a similar range of dust attenuation as these low-redshift LAEs.

##### 4.1. ISM Geometry

The geometry of the ISM can play a strong role in the escape of  $\text{Ly}\alpha$  photons.  $\text{Ly}\alpha$  photons are resonantly scattered

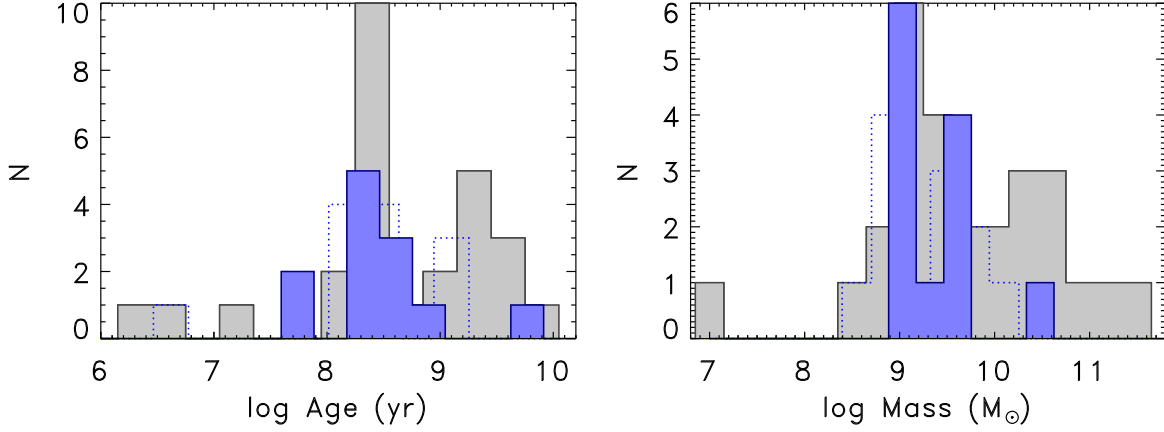


FIG. 3.— Left: Distribution of best-fit stellar populations ages for the 27 LAEs from Finkelstein et al. (2009a) are shown as the gray histogram. The best-fit ages we derive here for the subsample of 12 star-forming LAEs are shown as the blue histogram. While the original sample of 27 LAEs had many objects with best-fit ages  $> 1$  Gyr, when we exclude now-known AGNs from Finkelstein et al. (2009b), we find that all but one galaxy appears younger than 1 Gyr. The dotted blue histogram denotes the ages for the same 12 LAEs from Finkelstein et al. (2009a), which broadly agree with our updated results. Right: Same as the left, for the derived stellar masses. Similar to the ages, a smaller characteristic mass appears likely for these low-redshift LAEs once known AGNs are excluded.

TABLE 2  
SED FITTING RESULTS

Object	$m_{FUV}$ (mag)	$m_{NUV}$ (mag)	$m_u$ (mag)	$m_g$ (mag)	$m_r$ (mag)	$m_i$ (mag)	$m_z$ (mag)	$f_{Ly\alpha}/10^{-15}$ ( $\text{erg s}^{-1} \text{cm}^{-2}$ )	Age Best-Fit (Myr)	Age 68% Range (Myr)	Mass Best-Fit ( $10^9 M_\odot$ )	Mass 68% Range ( $10^9 M_\odot$ )	$A_V$ Best-Fit (mag)	$A_V$ 68% Range (mag)
EGS7	21.63	21.29	21.31	20.88	20.57	20.45	20.48	2.8	450	260 – 800	1.3	1.2 – 1.5	0.32	0.08 – 0.57
EGS8	22.03	21.66	21.88	21.18	20.76	20.64	20.63	1.5	320	140 – 400	1.6	1.6 – 2.1	0.00	0.00 – 0.40
EGS10	21.59	21.29	21.45	21.02	20.75	20.64	20.60	2.9	570	320 – 900	1.6	1.3 – 1.7	0.32	0.00 – 0.49
EGS11	22.16	21.77	21.34	20.58	20.07	19.85	19.73	1.4	290	80 – 360	3.8	3.7 – 4.9	0.49	0.32 – 1.05
EGS12	21.64	21.35	21.14	20.42	19.93	19.76	19.64	2.5	320	90 – 2600	4.9	4.8 – 5.8	0.49	0.16 – 0.89
EGS13	21.76	21.23	21.24	20.61	20.13	19.93	19.80	2.1	810	400 – 2600	4.2	3.8 – 7.3	0.57	0.16 – 0.81
EGS19	21.86	21.29	21.28	20.53	20.03	19.82	19.67	2.2	320	180 – 4200	4.9	4.8 – 10.8	0.57	0.16 – 0.89
EGS20	22.02	21.64	21.71	21.21	20.81	20.74	20.66	1.8	720	230 – 1600	2.0	1.7 – 2.0	0.32	0.08 – 0.49
EGS21	21.75	21.28	21.11	20.30	19.58	19.29	19.11	1.9	9000	2600 – 8800	34.4	10.5 – 33.7	0.00	0.00 – 0.65
EGS22	21.99	21.49	21.32	20.62	20.02	19.82	19.67	1.7	260	160 – 3500	4.8	4.7 – 4.9	0.65	0.24 – 0.89
EGS23	21.88	21.37	21.50	21.15	20.82	20.63	20.55	2.9	80	27 – 570	1.1	1.1 – 2.0	0.97	0.32 – 1.38
EGS25	22.18	21.10	21.44	21.17	20.95	20.87	20.65	2.6	60	18 – 71	1.2	1.2 – 2.2	0.97	0.89 – 1.46

NOTE. — These magnitudes have had all emission lines detected at  $\geq 3\sigma$  subtracted. The magnitude errors are 0.2 and 0.02 mag in the GALEX and optical bands, respectively (see Finkelstein et al. (2009a)).

by H I, thus in a homogeneous geometry (i.e. a dust screen in front of the sources), where H I gas and dust are evenly mixed, Ly $\alpha$  has a difficult time escaping, and thus has a much greater chance of encountering a dust grain than the continuum photons. On the other hand, if the ISM is inhomogeneous, with the dust locked together with neutral gas in many clumps residing in a tenuous, ionized medium, the Ly $\alpha$  photons will resonantly scatter at the edge of these clumps and avoid the dust, while the continuum light will pass through and be subject to dust attenuation (Neufeld 1991; Hansen & Oh 2006). This has the net effect of increasing the Ly $\alpha$  escape fraction over that of the continuum, and thus increasing the Ly $\alpha$  equivalent width (EW). This has been used to explain the large number of high Ly $\alpha$  EW LAEs which have been found (e.g., Kudritzki et al. 2000; Malhotra & Rhoads 2002). In Finkelstein et al. (2008) and Finkelstein et al. (2009d), we included this scenario in our stellar population models. We parameterized the ISM geometry with a free parameter “ $q$ ”, which is defined by

$$f'_{Ly\alpha} = f_{Ly\alpha} \times \exp(-q\tau_c) \quad (1)$$

where  $\tau_c$  is the optical depth of dust on the continuum light, thus  $q = \tau_{Ly\alpha}/\tau_c$ . We make the assumption that the covering fraction of clumps is large, meaning that a Ly $\alpha$  photon will scatter many times prior to escape. In this scenario, the extinction curve (which we assume to be that of Calzetti et al. (2000)) is the same as that for a uniform dust screen (Scarlata et al. 2009), excepting that Ly $\alpha$  photons can preferentially avoid encountering the dust. When  $q = 10$ , this has the effect of a homogeneous ISM, where Ly $\alpha$  is attenuated far more than the continuum as resonant scattering increases the chance of absorption by dust. When  $q = 0$ , this simulates the Neufeld (1991) scenario, where all of the dust is locked away inside neutral gas clumps. In between values of  $q$  reflect intermediate geometries, with any value of  $q < 1$  enhancing the Ly $\alpha$  EW. Using this, we found that dust enhancement can explain the SEDs of many  $z \sim 4.5$  LAEs, as 10/14 objects had  $q < 1$ . We also used the ISM clumpiness parameter  $q$  when we fit models in Finkelstein et al. (2009a) and §3 to the present sample. Our 12 low-redshift LAEs have a best-fit range from  $0 \leq q \leq 1$ , with 5/12 objects having  $q$  from 0.75 – 1.0 (using the updated model fitting results discussed in §3), reflecting an ISM which does not much enhance



or attenuate the Ly $\alpha$  EWs.

With these spectroscopic data, we can now perform a more in depth analysis into the ISM geometry by comparing the resonantly scattered Ly $\alpha$  line to a non-resonant line, such as H $\alpha$ , as a proxy to trace the continuum photons. Under Case B recombination, the intrinsic ratio of Ly $\alpha$ /H $\alpha$  is  $\sim 8.7$ . Any deviation from this value is presumably due to dust (although preferential scattering of Ly $\alpha$  photons could play a role). In a typical homogeneous ISM, this value will drop quickly if dust is present. If, however, the ISM is in a configuration that results in the enhancement of the Ly $\alpha$  EW, this value will increase.

Our H $\alpha$  measurements come from a 1.5'' diameter fiber, while the Ly $\alpha$  measurements are from the far-ultraviolet (FUV) *GALEX* prism, which has a beam full-width at half-maximum (FWHM) of 4.2'' (Morrissey et al. 2007). As many of these galaxies are larger than 1.5'' (see Figure 1 of Finkelstein et al. (2009a)), we need to account for aperture differences between the Ly $\alpha$  and H $\alpha$  measurements. We did this by first measuring photometry of our sample of galaxies in the Canada–France–Hawaii–Telescope Legacy Survey (CFHTLS) *i'* image (which has a seeing of  $\sim 0.7''$ , comparable to our Hectospec observations), using an aperture diameter of the same size as the Hectospec fibers (1.5''). We then smoothed this image such that the FWHM of stars in the image matched the FWHM of the *GALEX* beam, and performed photometry on our sample again, this time using 4.2'' diameter apertures. In both cases, the photometry was done using the Source Extractor software package (Bertin & Arnouts 1996). The aperture correction which we applied to the H $\alpha$  flux measurement is thus the ratio of the flux in the 4.2'' aperture to that in the 1.5'' aperture. This aperture correction factor ranged from 1 – 4, with a median of 1.3, and 11/12 galaxies having an aperture correction factor of  $< 2.0$  (one object had a correction of  $< 1$ , which we rounded up to 1).

The top panel in Figure 4 plots the Ly $\alpha$ /H $\alpha$  ratios, using the aperture correction, for our sample versus their derived dust attenuation from the previous section. Examining first the Ly $\alpha$ /H $\alpha$  ratios, we find they span  $1 < \text{Ly}\alpha/\text{H}\alpha < 7$ , with all 12 objects having line ratios significantly less than 8.7, implying dust is likely present. However, the exact amount of dust cannot be derived from this ratio alone as the geometry plays a role. Using stellar population models from Finkelstein et al. (2009a), we also plot tracks of constant ISM clumpiness, from  $q = 0 - 10$ . Thus, by examining where our objects fall in this plane, we can gain insight into their ISM geometry.

Investigating this plane, we find that the majority of our objects are consistent with values of  $q \sim 1-3$ . This implies that the dust that is present lies in a geometry somewhere between that of a uniform screen and that of purely clumps. In the bottom panel of Figure 4, we plot the *GALEX* derived Ly $\alpha$  EW versus the attenuation we derive here. We see that the Ly $\alpha$  is between 20 – 40 Å for most objects regardless of the level of extinction. This again implies that the ISM is neither overtly enhancing nor depleting the Ly $\alpha$  EW (similar also to the results from SED fitting). Similar results are seen at  $z \sim 2$ , where Blanc et al. (2010) recently analyzed a sample of  $\sim 100$  LAEs and found that Ly $\alpha$  and the rest-frame UV continuum experienced similar levels of extinction (i.e.  $q = 1$ ). As mentioned above, Finkelstein et al. (2009d) found that many  $z \sim 4.5$  LAEs were consistent with  $q \leq 1$ , thus at much higher redshift the ISMs may be more clumpy, though this was indirectly inferred via SED fitting.

Atek et al. (2009) studied the escape fraction of Ly $\alpha$  pho-

tons in their sample of  $z \sim 0.3$  LAEs, finding that some objects indicate Ly $\alpha$ -assisted escape due to a clumpy ISM ( $q < 0$ ), some objects appear to have similar Ly $\alpha$  and UV-continuum escape fractions ( $q \sim 1$ ), and some objects have Ly $\alpha$  escape fractions  $<$  the UV continuum ( $q > 1$ ). Scarlata et al. (2009) recently investigated the ISMs of LAEs from the Deharveng et al. (2008) sample, examining a number of radiative transfer scenarios, including a clumpy ISM. In particular, they study how the hydrogen line ratios change with the number of clumps, deducing that they have clumpy interstellar media. However, these authors also conclude that there is no evidence for preferential shielding of Ly $\alpha$  from dust, as they do not have any objects with Ly $\alpha$ /H $\alpha$   $> 8.7$ , similar to our results. Scarlata et al. note that the attenuation curve in a clumpy ISM can differ from that for the uniform dust screen if the number of clumps are small. Thus although we have assumed a large number of clumps such that the uniform dust screen law applies in our above discussion, this need not be the case.

Examining the results for all studied *GALEX* LAEs, it appears that although the ISMs in low-redshift analog LAEs span a wide range of extinction and clumpiness values, some level of clumping appears likely (i.e., a uniform dust screen does not appear to be supported by the data). We note that the necessity of an aperture correction based on photometric data adds a level of overall uncertainty, as it assumes the H $\alpha$  flux is spatially correlated with the broadband emission. This can be avoided in future studies when both lines are measured in similar apertures.

## 5. MASS-METALLICITY RELATION

Using our measured emission lines, we can measure the gas-phase metallicities of the galaxies in our sample with a number of metallicity indices. We can then examine these galaxies on a mass-metallicity relation to see how they compare to other populations. We use ratios of emission lines of oxygen and nitrogen to those of hydrogen to measure the gas-phase metallicities of the galaxies in our sample. Specifically, we use the calibrations of the N2 and O3N2 indices of Pettini & Pagel (2004), where

$$\text{N2} = \log \left( \frac{[\text{NII}]}{\text{H}\alpha} \right) \quad (2)$$

and

$$\text{O3N2} = \log \left( \frac{[\text{OIII}]\lambda 5007 / \text{H}\beta}{[\text{NII}] / \text{H}\alpha} \right). \quad (3)$$

Additionally, we obtain another measure of the metallicity using the well-known R23 index, where

$$R_{23} = \frac{[\text{OII}]\lambda 3727 + [\text{OIII}]\lambda 4959, 5007}{\text{H}\beta}, \quad (4)$$

using the calibration of Kobulnicky et al. (1999). This index is double valued above  $Z \sim 0.3 Z_{\odot}$ , thus we tabulated the metallicities for both the upper and lower branches. Table 4 presents the measured metallicities of our galaxies from each of these indices, as well as their errors, including systematic uncertainties from the calibrations of 0.05, 0.14 and 0.18 dex for R23, O3N2 and N2 indices, respectively. We note that these indices were calibrated using nearby galaxies, and they may be sensitive to a change in H II region physical conditions such as the ionization parameter or electron temperature. In fact, many high-redshift star-forming



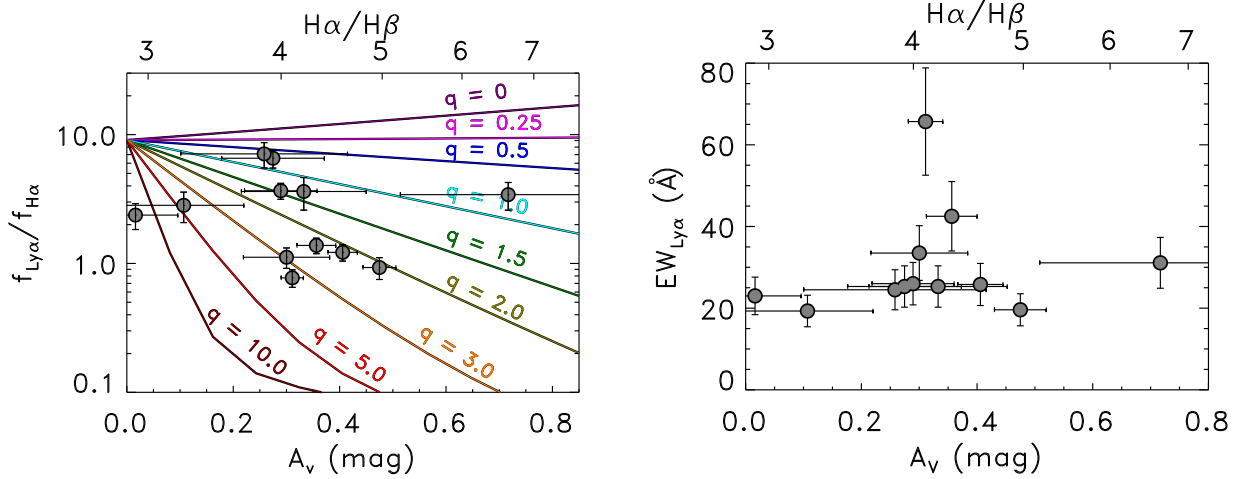


FIG. 4.— Left: The distribution of Ly $\alpha$ /H $\alpha$  ratios versus the measured dust attenuation for the 12 star-forming LAEs in our sample. The values of Ly $\alpha$ /H $\alpha$  have been corrected for aperture differences. The colored lines show model tracks for constant values of  $q$ , the ISM clumpiness factor. By studying our objects in this plane, we see that few appear to have an ISM geometry that preferentially favors Ly $\alpha$  escape over continuum photons. Most of the sample lies at  $q \sim 1$ –3, implying that Ly $\alpha$  encounters a similar level of dust (and possibly a bit more) than the continuum. Right: The Ly $\alpha$  EW versus the derived dust attenuation. The EW is roughly invariant to the level of dust, implying that the ISMs of these objects are neither strongly enhancing nor depleting the Ly $\alpha$  EWs, and thus that neither a uniform dust screen, or a purely clumpy ISM geometry apply to these objects.

TABLE 3  
MEASURED DUST EXTINCTION AND GAS-PHASE METALLICITIES

Object	$E(B-V)_{\text{gas}}$	$A_{V,\text{stellar}}$ (mag)	$Z_{\text{N2}}$ ( $Z_{\odot}$ )	$Z_{\text{O3N2}}$ ( $Z_{\odot}$ )	$Z_{\text{R23}}^l$ ( $Z_{\odot}$ )	$Z_{\text{R23}}^u$ ( $Z_{\odot}$ )	Z Weighted Mean ( $Z_{\odot}$ )
EGS7	$0.23 \pm 0.02$	$0.41 \pm 0.04$	$0.30 \pm 0.13$	$0.27 \pm 0.09$	$0.18 \pm 0.03$	$0.68 \pm 0.11$	$0.20 \pm 0.03$
EGS8	$0.06 \pm 0.06$	$0.11 \pm 0.11$	$0.26^{\dagger}$	$0.29^{\dagger}$	$0.20 \pm 0.12$	$0.86 \pm 0.36$	$0.25 \pm 0.07$
EGS10	$0.16 \pm 0.04$	$0.29 \pm 0.07$	$0.18^{\dagger}$	$0.23^{\dagger}$	$0.28 \pm 0.11$	$0.66 \pm 0.20$	$0.22 \pm 0.05$
EGS11	$0.19 \pm 0.07$	$0.33 \pm 0.12$	$0.85 \pm 0.38$	$0.73 \pm 0.26$	$0.23 \pm 0.17$	$1.11 \pm 0.46$	$0.44 \pm 0.13$
EGS12	$0.15 \pm 0.05$	$0.27 \pm 0.10$	$0.54 \pm 0.24$	$0.48 \pm 0.17$	$0.24 \pm 0.13$	$0.90 \pm 0.33$	$0.36 \pm 0.10$
EGS13	$0.27 \pm 0.02$	$0.47 \pm 0.04$	$0.58 \pm 0.24$	$0.53 \pm 0.17$	$0.24 \pm 0.05$	$0.96 \pm 0.15$	$0.28 \pm 0.05$
EGS19	$0.17 \pm 0.05$	$0.30 \pm 0.08$	$0.87 \pm 0.38$	$0.81 \pm 0.28$	$0.17 \pm 0.09$	$1.31 \pm 0.34$	$0.26 \pm 0.08$
EGS20	$0.01 \pm 0.04$	$0.02 \pm 0.08$	$0.31^{\dagger}$	$0.31^{\dagger}$	$0.25 \pm 0.11$	$0.73 \pm 0.24$	$0.28 \pm 0.07$
EGS21	$0.14 \pm 0.09$	$0.26 \pm 0.16$	$1.13 \pm 0.53$	$1.33 \pm 0.52$	$0.14 \pm 0.14$	$1.74 \pm 0.66$	$1.36 \pm 0.33$
EGS22	$0.40 \pm 0.11$	$0.72 \pm 0.21$	$0.31^{\dagger}$	$0.52^{\dagger}$	$0.38 \pm 0.59$	$1.07 \pm 0.85$	$0.38 \pm 0.13$
EGS23	$0.20 \pm 0.02$	$0.36 \pm 0.04$	$0.49 \pm 0.21$	$0.41 \pm 0.13$	$0.22 \pm 0.05$	$0.80 \pm 0.14$	$0.26 \pm 0.05$
EGS25	$0.17 \pm 0.01$	$0.31 \pm 0.03$	$0.33 \pm 0.14$	$0.28 \pm 0.09$	$0.14 \pm 0.02$	$0.73 \pm 0.10$	$0.15 \pm 0.02$

NOTE. —  $^{\dagger}$  [N II] was undetected in EGS8, EGS10, EGS20 and EGS22, and the  $3\sigma$  upper limit was used on the line flux to compute N2 and O3N2. N2 is thus an upper limit and O3N2 is a lower limit. The weighted mean metallicity was computed with just one value for R23 per object, using the value which gave the lowest error on the weighted mean with the N2 and O3N2 metallicities (which ended up being the lower branch in all cases). The exception is EGS21, where although the weighted mean uncertainty was formally smaller with the lower R23 result, the high metallicities with the O3N2 and N2 indices imply that the upper branch is correct.

galaxies may have an increased ionization parameter as they appear enhanced in [O III]/H $\beta$  from the local star-forming galaxies sequences from the SDSS (e.g., Erb et al. 2006b; Finkelstein et al. 2009c; Hainline et al. 2009). However, as shown in Finkelstein et al. (2009b) the star-forming members of our sample have similar [O III]/H $\beta$  ratios as the SDSS galaxies, thus they likely have similar H II region properties as well.

Prior to this computation, the emission lines were corrected for the inferred dust extinction from §4. We also present a weighted mean metallicity from all three measures, where the R23 value which results in smaller uncertainty on the weighted mean was chosen (with the exception of EGS21, where it is obvious that the upper branch of R23 is the appropriate one). In nearly all cases, the three measures of the metallicities are consistent within their uncertainties, thus our results are not dependent on the precise indices used. Investi-

gating Table 3, we find that these low-redshift LAEs typically have metallicities from  $0.2 - 0.4 Z_{\odot}$ .

In Figure 5, we plot the 12 star-forming  $z \sim 0.3$  LAEs in a mass-metallicity plane. Star-forming galaxies were extensively studied in this plane by Tremonti et al. (2004), who used SDSS spectra of  $\sim 53,000$  star-forming galaxies to study the mass-metallicity relation at  $z \sim 0.1$ . In that work, they computed the metallicities by using a combination of all strong emission lines. Because different metallicity indicators suffer inherent systematic uncertainties of  $0.2 - 0.6$  dex (Kewley & Dopita 2002; Tremonti et al. 2004; Moustakas et al. 2010), we recomputed metallicities for the SDSS sample using the same techniques as above. In Figure 5 we show the best-fit mass-metallicity relation of Tremonti et al. (2004), which is shifted downward by 0.1 dex to match our recomputed SDSS metallicities.

At any given mass, all but the most massive of our  $z \sim$

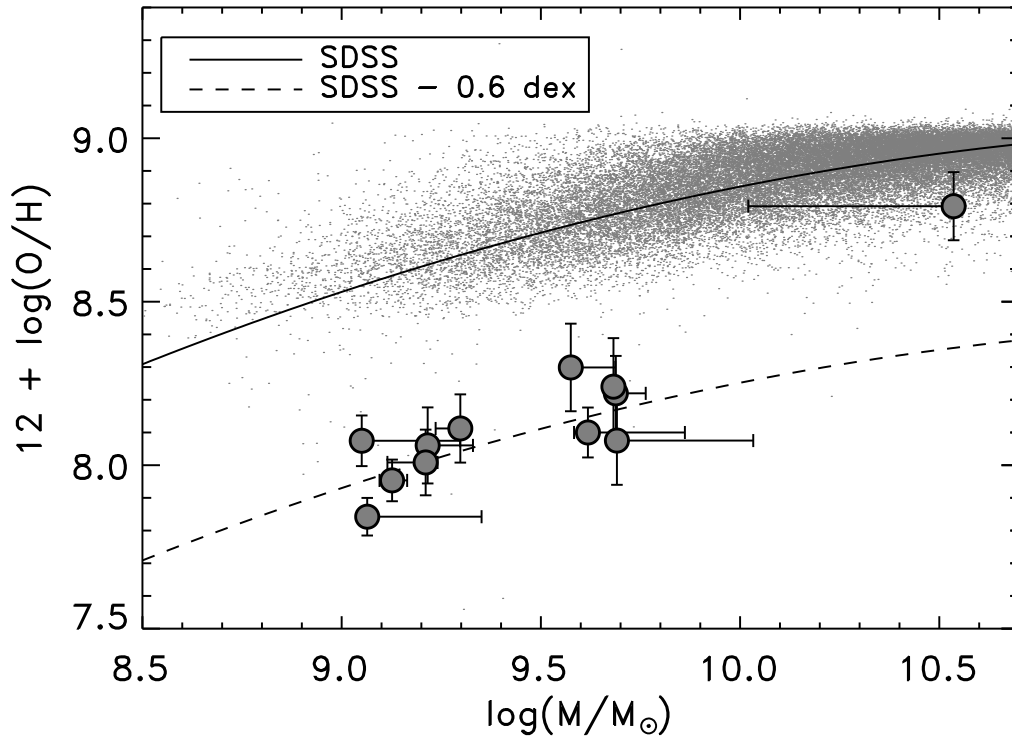


FIG. 5.— Our sample of 12 star-forming low-redshift LAE analogs plotted in a mass-metallicity plane. For comparison, we show the sample of  $\sim 53,000$  SDSS galaxies from Tremonti et al. (2004), where we recomputed their metallicities using the same methods as our sample. The solid line is the best-fit mass-metallicity relation from Tremonti et al. (2004) (shifted down 0.1 dex to match the sequence shown using our metallicity derivation). The dashed line is the SDSS relation shifted downward by  $\sim 0.6$  dex, highlighting that these LAE analogs are significantly shifted downward in metallicity for a given mass when compared to the SDSS sample. This implies that galaxies exhibiting Ly $\alpha$  in emission may be systematically more metal poor than other galaxies at the same stellar mass and redshift.

0.3 LAEs lie significantly below the  $z \sim 0.1$  mass-metallicity relation. In Figure 5, we show the best-fit curve to the  $z \sim 0.1$  mass-metallicity relation from Tremonti et al. (2004) shifted to match our derived SDSS metallicities, and we find that shifting it downward by a further  $\sim 0.6$  dex best matches our sample of LAEs. This offset is larger than plausible errors in the stellar masses. This illustrates that at low-redshift, galaxies exhibiting Ly $\alpha$  in emission have significantly lower metallicities than comparable mass galaxies with no such pre-selection. Cowie et al. (2010) found similar results, as they noted that *GALEX*-selected LAEs had lower metallicities than star-forming galaxies selected via the near-UV continuum. However, their brighter LAEs had similar metallicities to their continuum-selected sample, while all but one of our more massive LAEs are still more metal-poor than the SDSS sample. The differences may be due to the use of solely the N2 index in Cowie et al. (2010), as it typically yields the highest metallicities of the three indicators we use in our sample.

At  $z \sim 0.3$  the mass-metallicity relation of LAEs is shifted lower than that of the SDSS galaxies, which represent the general star-forming galaxy population at these redshifts. At high redshift, LBGs appear to be the dominant galaxy population. Erb et al. (2006b) has studied the mass-metallicity relation of LBGs at  $z \sim 2.3$ , finding that their objects fit the shape of the local mass-metallicity relation, but shifted downward in metallicity by 0.56 dex (over a metallicity range of  $0.4 - 0.9 Z_{\odot}$  for galaxies with stellar masses of  $10^9 - 10^{11} M_{\odot}$ ). Current results show that high-redshift LAEs are on average less evolved in age, mass and dust content than LBGs (e.g.,

Gawiser et al. 2006; Finkelstein et al. 2009d; Pentericci et al. 2009), thus it may seem intuitive that they would be lower in metallicity as well (i.e., less evolved in all physical characteristics), possibly shifted even further down for the LBG mass-metallicity relation.

This was recently studied at high-redshift by Finkelstein et al. (2010), where upper limits on the metallicities of two LAEs at  $z = 2.3$  and  $2.5$  were measured to be  $Z < 0.17$  and  $0.28 Z_{\odot}$ , respectively, with the N2 index. The object with the lower metallicity upper limit appears to be significantly below even the  $z = 2.3$  LBGs of Erb et al. (2006b) on the mass-metallicity relation, analogous to our results at  $z \sim 0.3$ . At  $z = 2.3$ , LBGs represent the general star-forming galaxy population, and LAEs appear to be more metal-poor than this population (though with a sample of two objects we cannot draw robust conclusions). However, we see something very similar at  $z \sim 0.3$ , where the SDSS sample represents the general star-forming galaxy population. Thus, it may be that galaxies exhibiting Ly $\alpha$  in emission have preferentially lower metallicities. However, the evidence for this at high redshift is not strong, and a confident resolution will not be possible until we can measure the metallicities of large samples of high-redshift LAEs, which will be done in the near future with the upcoming multi-object NIR spectrographs.

## 6. CONCLUSIONS

We present results from a spectroscopic survey of *GALEX*-discovered LAEs at  $z \sim 0.3$ . These objects are useful as nearby analogs to high-redshift LAEs, as we are able to di-

rectly measure physical quantities which are only inferred at high-redshift. In this Paper, we present the full optical spectra of 12 star-forming LAEs, including hydrogen, oxygen and nitrogen line fluxes. We first re-examine their stellar population properties, and find that when excluding the recently identified AGNs in the parent sample, the average ages and masses of the remaining star-forming LAEs are lower, at  $\sim 300$  Myr and  $4 \times 10^{10} M_{\odot}$  respectively. These are older and more massive than a typical high-redshift LAE, but similar to a rare population of evolved high-redshift LAEs.

Correcting our measured emission line fluxes for stellar absorption, we use the Balmer decrement to investigate the level of dust attenuation in these galaxies. We find that these galaxies all contain some level of dust, with an average extinction of  $A_V \sim 0.3$  mag. This is similar to what is typically found at high redshift, and is also consistent with the overall trend of the existence of dust in galaxies which are still able to emit in Ly $\alpha$ . Using the ratio of Ly $\alpha$ /H $\alpha$  and the measured extinction as a probe of the ISM geometry, we find that in general the ISM geometries for the majority of the sample appear to be somewhere between homogeneous and purely clumpy, implying that a uniform dust screen geometry does not apply to these objects.

Lastly, we use three different metallicity indicators to measure the gas-phase metallicities of the LAEs in our sample.

We find that all but one of these galaxies have lower metallicities than field galaxies at the same stellar mass, with typical gas-phase metallicities of  $\sim 0.2 - 0.4 Z_{\odot}$ . Comparing to recent results at high-redshift, it appears that galaxies exhibiting Ly $\alpha$  in emission may be systematically more metal poor at all redshifts, though more work is needed.

Studying LAEs spectroscopically allows us to learn about their physical properties in more detail and with greater confidence than with stellar population model fitting. Ideally, these low-redshift LAEs would be used as analogs to allow us to decipher the physical characteristics of high-redshift LAEs. As these objects studied here are more evolved than typical narrowband-selected high-redshift LAEs, we can only put limits on what we expect to find at high-redshift. However, with the numerous multi-object near-infrared spectrographs coming online soon, we can expect to make great progress in understanding LAEs by directly measuring their physical properties at  $z \sim 2 - 3$ .

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